Frontiers of TeV γ- Ray Astronomy

Narayana P. Bhat

UAH/NSSTC and

Tata Institute of Fundamental Research

Plan of the talk

- Introduction
- Atmospheric Cerenkov Technique
  - Imaging Technique
  - Wavefront Sampling Technique
- Background rejection methods
- Scientific Motivation & Recent Results relating to:
  - TeV emission from blazars,
  - Investigation of the inter-galactic IR fields,
  - SNR's: Sources of galactic cosmic rays,
  - Pulsar particle acceleration mechanisms,
  - Astro-particle as well as fundamental Physics related questions.
- Summary & future outlook

Introduction

- Astrophysically, the subject of γ-ray astronomy is the study of Nonthermal Universe.

  i.e. diffuse cosmic matter and radiation with an energy distribution that has no characteristic energy scale attributable to a temperature.

- So far, the Nonthermal Universe is pretty much terra incognita, and while the sources and collective acceleration mechanisms for particles of *TeV* energies and beyond are subject of much speculation and theoretical work.

- The experimental identification of sources and of acceleration mechanisms is lacking.
- Only a few - and possibly atypical - objects have been detected, and even less have been studied in any detail.
- In our Galaxy the energy density of cosmic rays (~1 eV/cc) is comparable to the energy density of starlight, of interstellar magnetic fields and of the kinetic energy density of interstellar gas.
- Nonlinear acceleration mechanisms transform a significant fraction (~10%) of the kinetic energy released in supernova explosions into energies of highly relativistic particles.

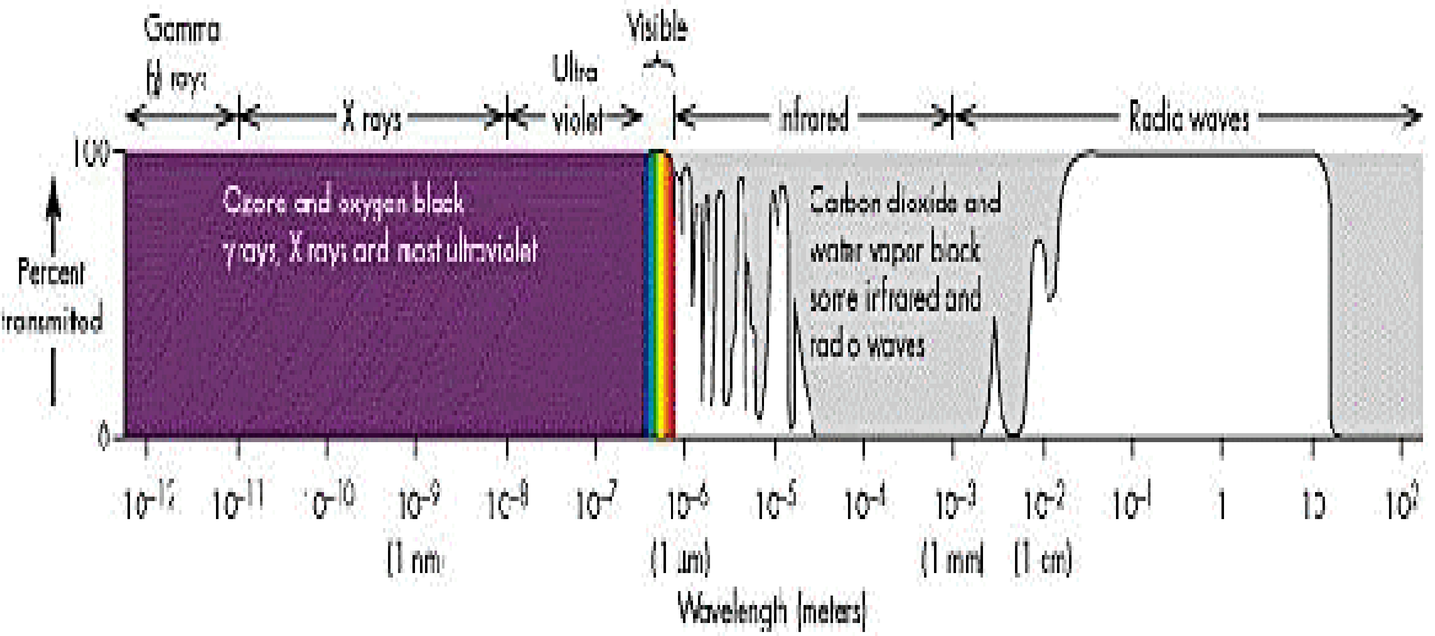
- Inter-play between cosmic rays and magnetic fields influences the evolution of galaxies.
- The theoretical understanding of high energy processes consists of:

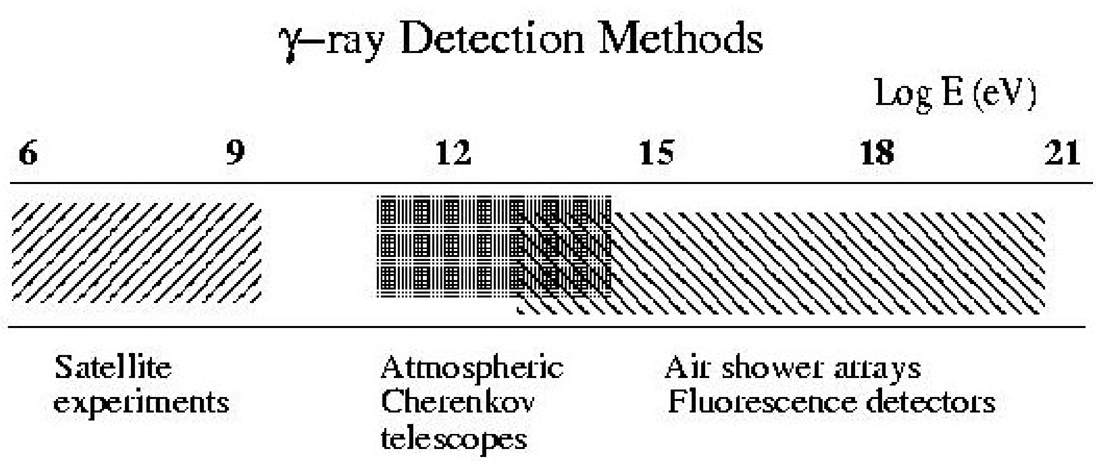
  a. relativistic outflow

  b. shock wave dissipation &

  c. particle acceleration
- The Nonthermal Universe is of significant importance for our understanding of the Universe, its objects, and their evolution.
- Compared to the charged particles, which are the primary products of cosmic accelerators, γ -rays have the substantial advantage that they propagate on straight lines through the universe.

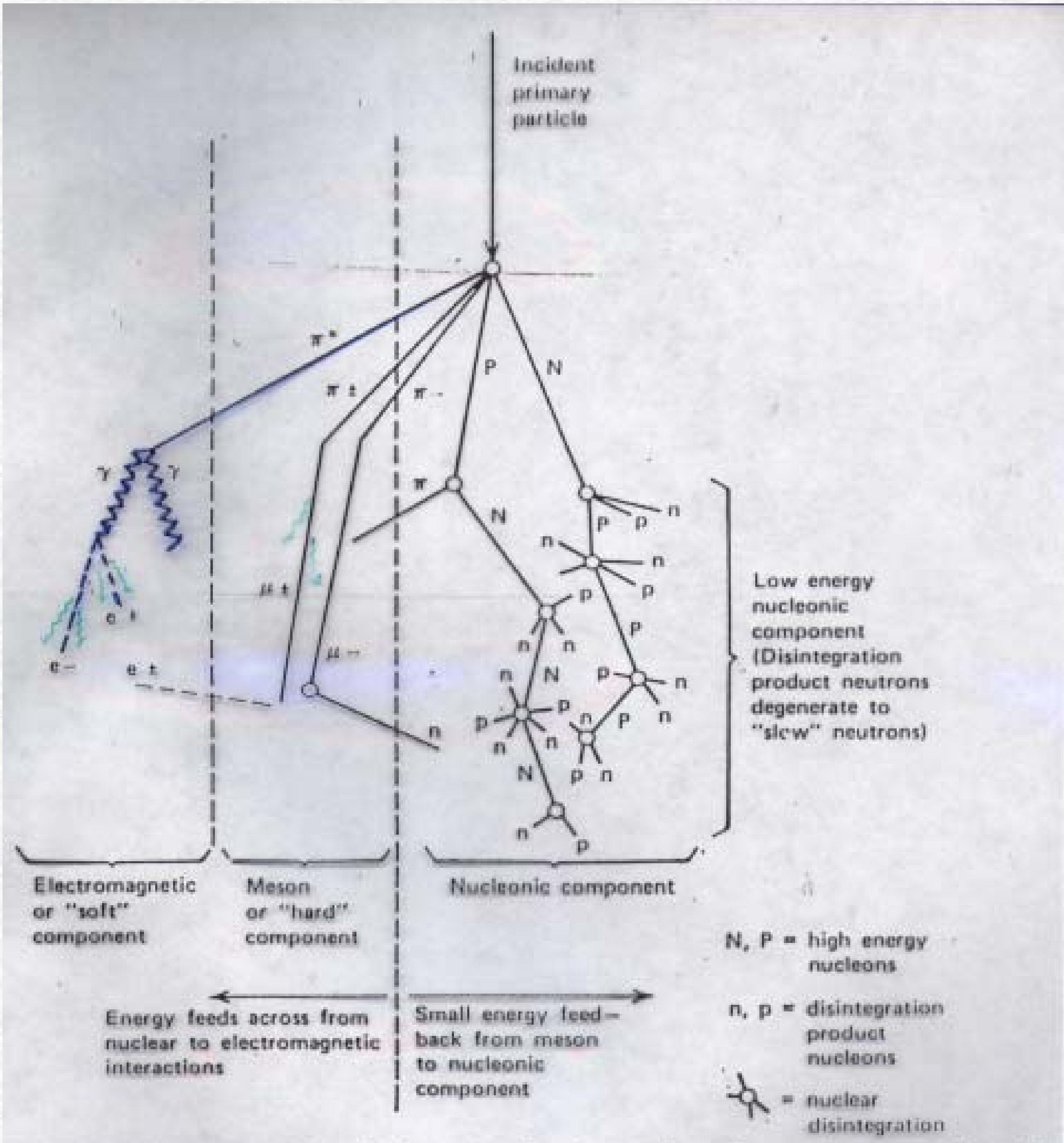
- The flux of γ– rays from a source region is governed by
    1. the density of their charged parent particles, multiplied by the density of the target used to generate γ–rays – the ambient medium,
    2. the energy density in magnetic fields, or
    3. the energy density in low-energy target photons for the inverse Compton process.
- The energy spectrum of γ–rays is closely related to the spectrum of the parent particles.
- γ– rays are least attenuated and hence provide a deep probe to the universe.





Gamma-ray detection methods. The ranges in energy covered by current gamma-ray detectors are shown. The horizontal axis is Log(E) where E is the energy in electron-Volts. The various detector techniques are discussed in the text. Results from experiments using the fluorescence technique are not included in this review.

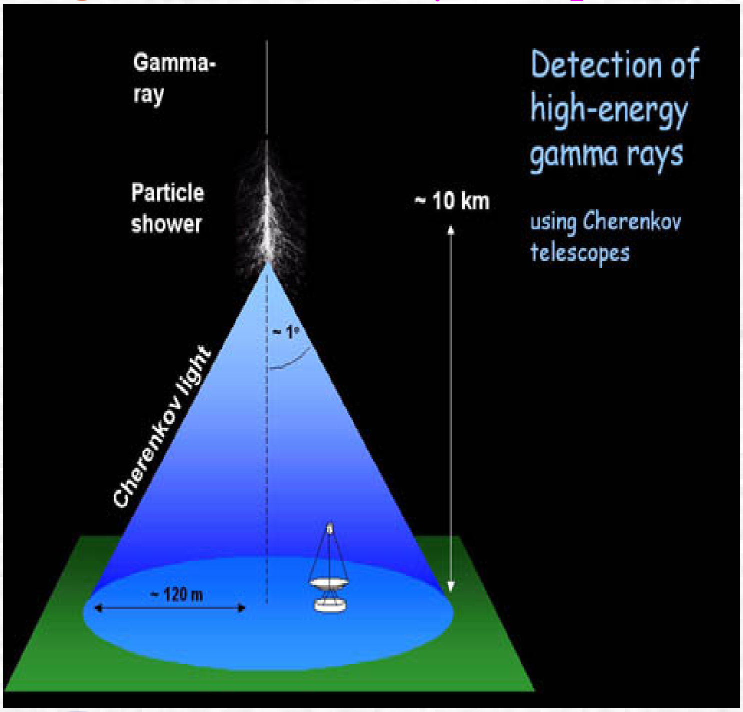
EAS Cascade in Earth's Atmosphere



Schematic representation of the results of an interaction of a cosmic ray particle with the atmosphere. (From Simpson, Fonger, and Treiman 1953, p. 936.)

The atmospheric Cerenkov Technique

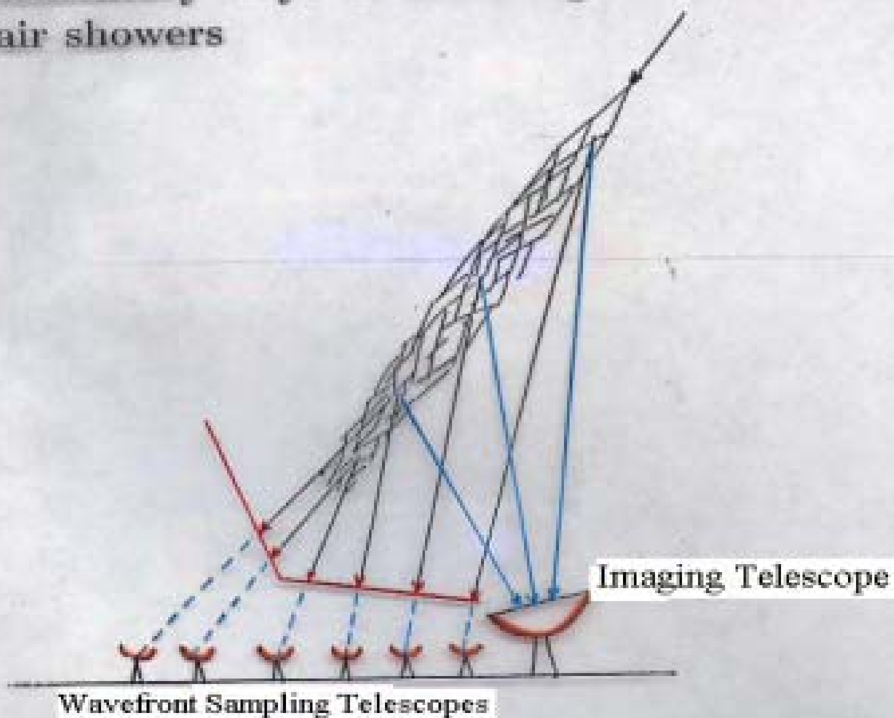
- The Cerenkov light pulse is fast (~ 5ns)
- The angular size of the beam on the ground is small (~ 1 deg.)
- The Cerenkov spectrum on ground peaks at blue so optical detection is possible.
- Due to the lateral spread, the light pool results in a large collection area (>40,000 m^2)
- The total # of photons is α primary energy
- However the challenging task is to distinguish between γ and p showers.



Atmospheric Čerenkov Technique

Wavefront Sampling vs Angular Imaging

Two complementary ways of detecting Čerenkov photons from air showers



Wavefront Sampling : Spectral and timing information of Čerenkov shower front is sampled at several points in Čerenkov pool

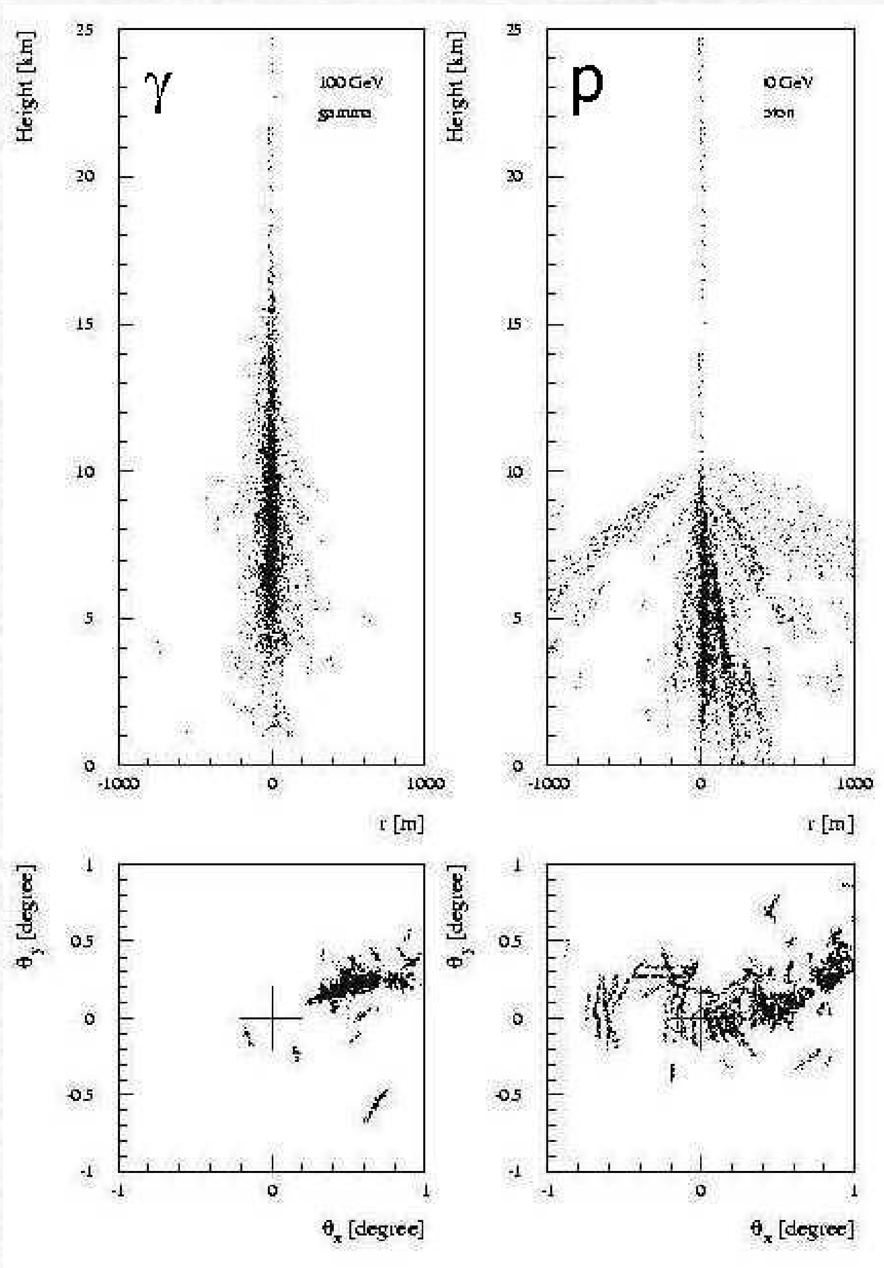
Imaging experiments : Whipple, CAT, HEGRA,

CANGAROO, Durham, TACTIC etc.

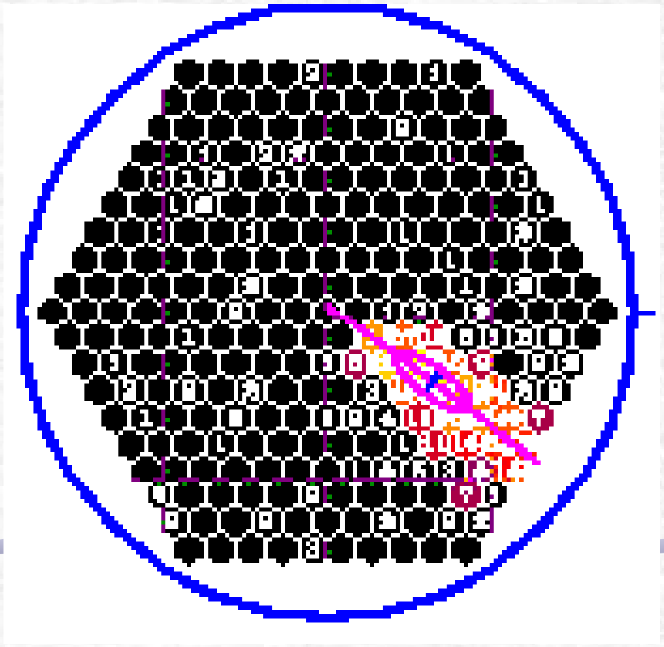
Wavefront sampling experiments : PACT, CELESTE,

STACEE, GRAAL

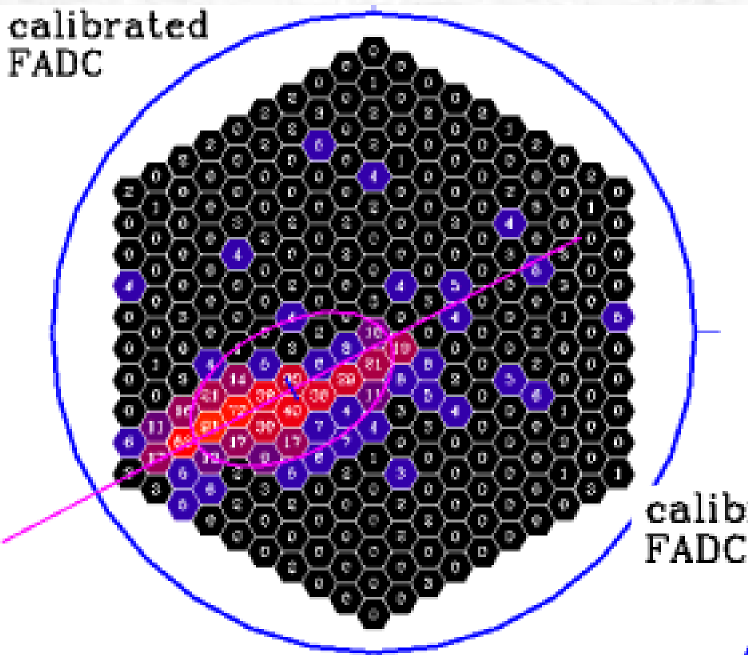
Cerenkov images generated by γ & p primaries

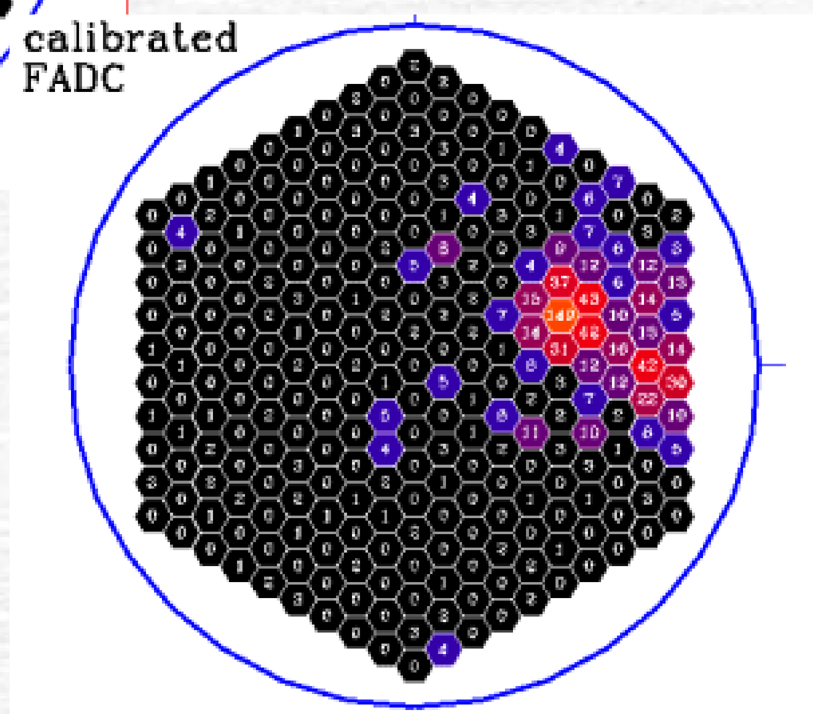


Whipple 10 m Telescope

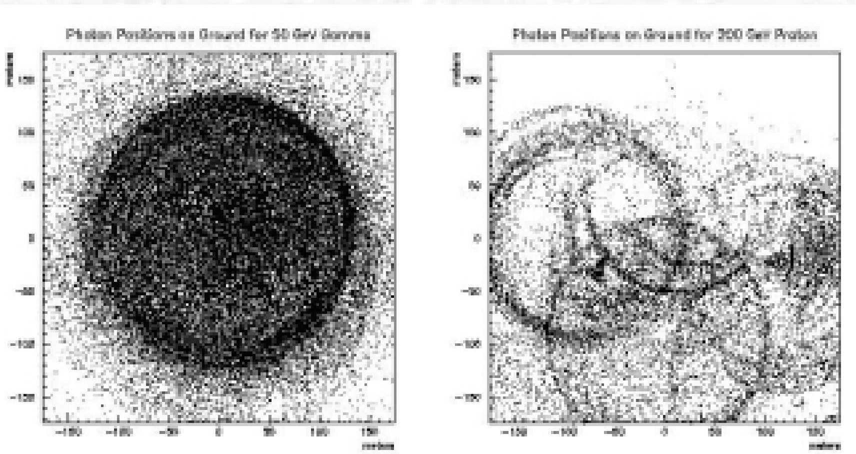


Examples of γ & p images

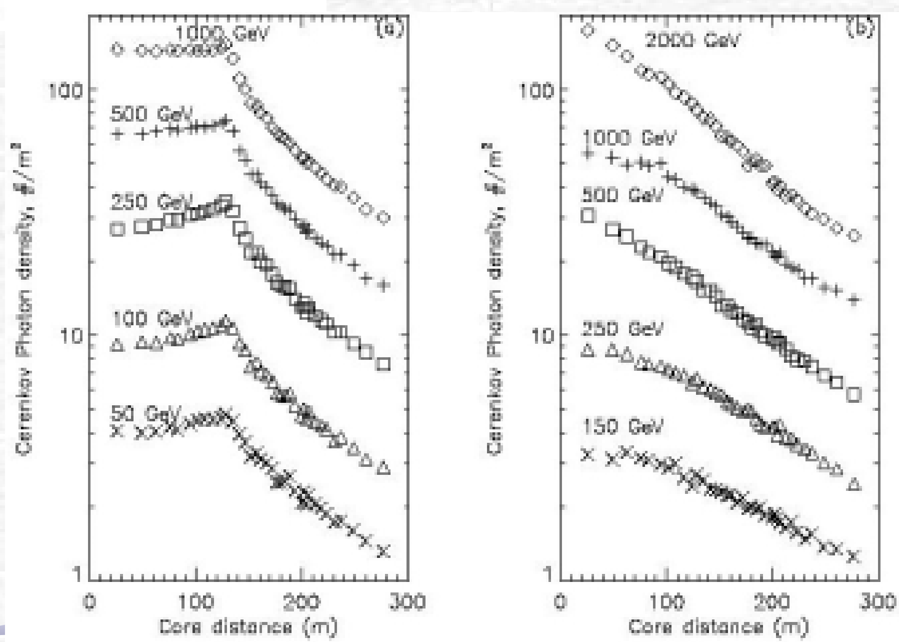




Cerenkov Photon Distribution on Ground

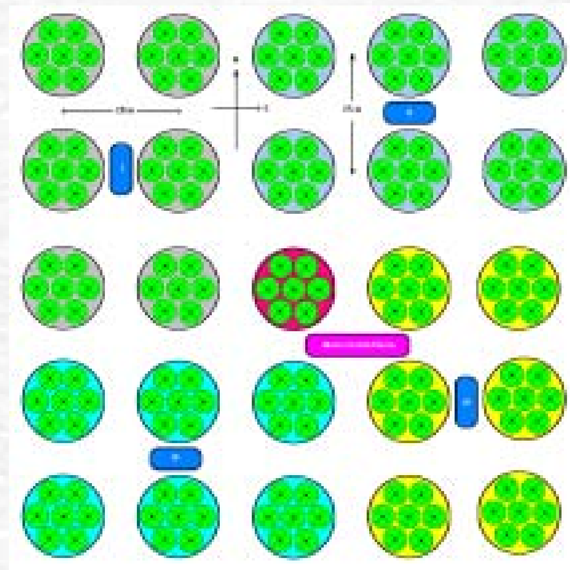


Comparison of the lateral distributions of the Cherenkov light in vertically incident gamma-ray and proton extensive air showers (from the simulation MOCCA [63]). The left shows the arrival positions on the ground of all Cherenkov photons produced in an air shower created by a single 50 GeV gamma ray. The right shows the same information for an air shower created by a single 200 GeV proton. The observation depth is $820\,\mathrm{g\,cm^{-2}}$.

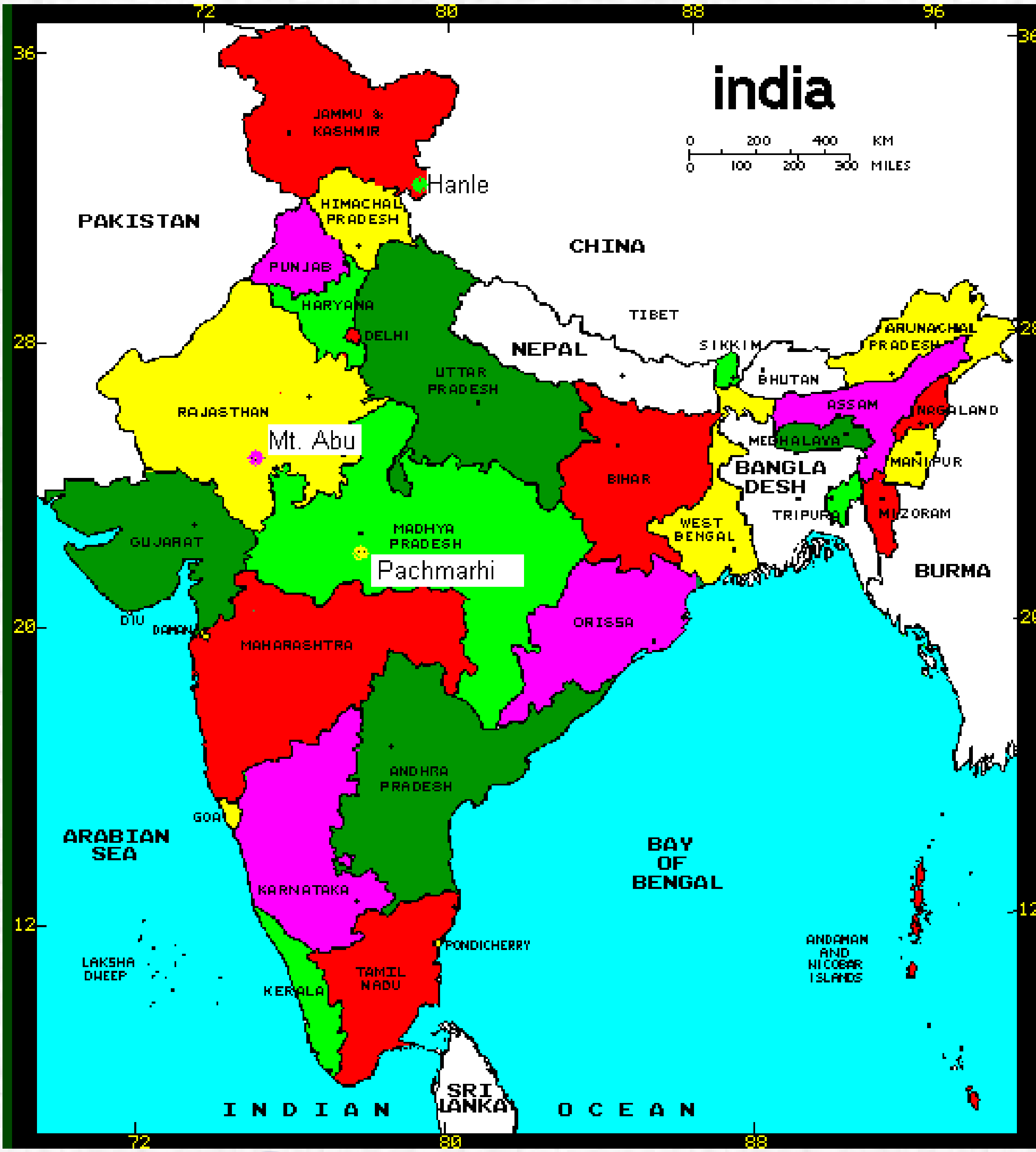


STACEE

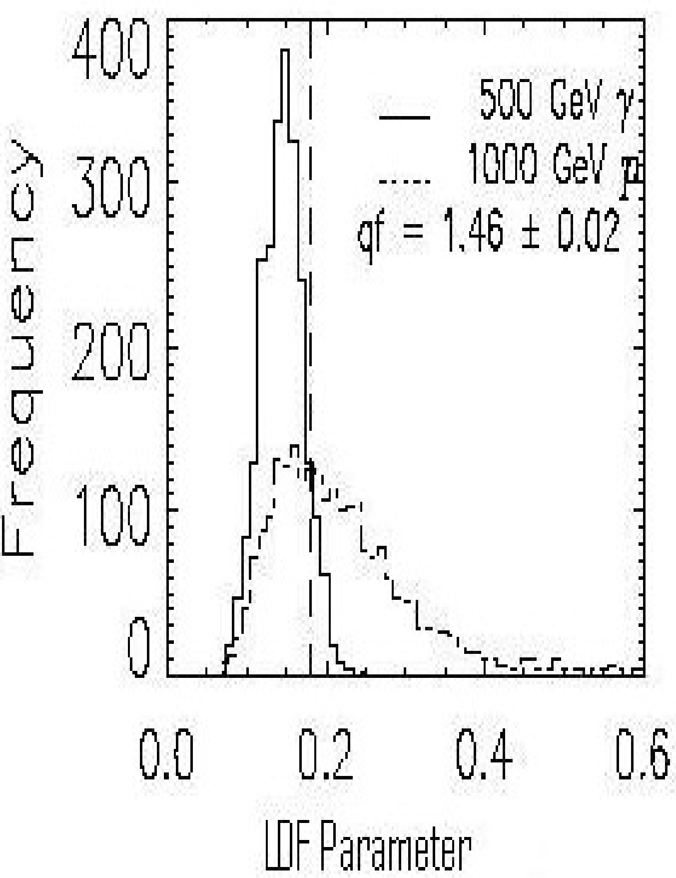
Pachmarhi Array of Cerenkov Telescopes (PACT)

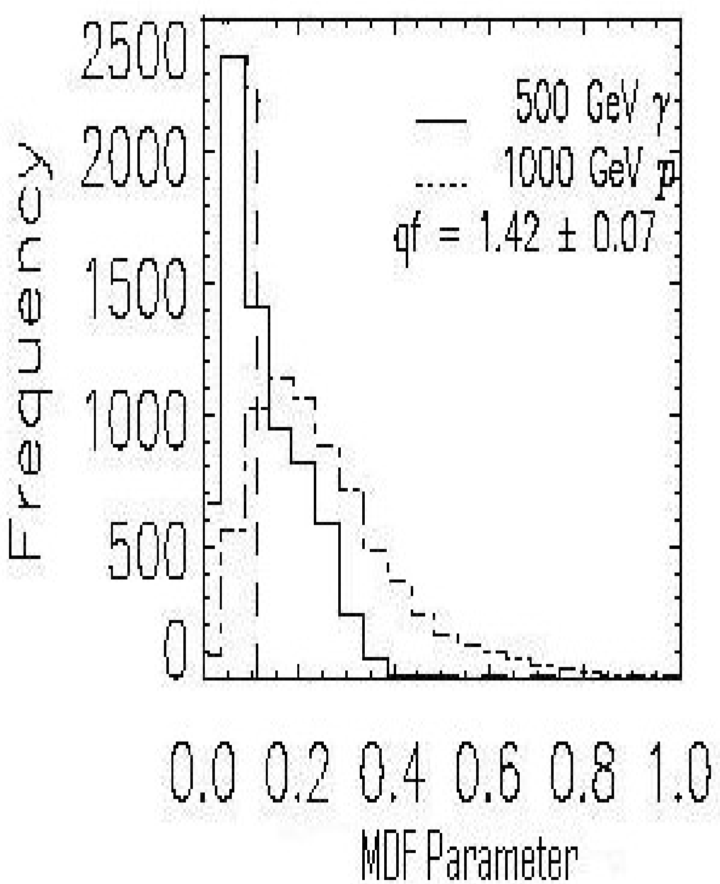


Locations of TeV γ-ray Observatories in India



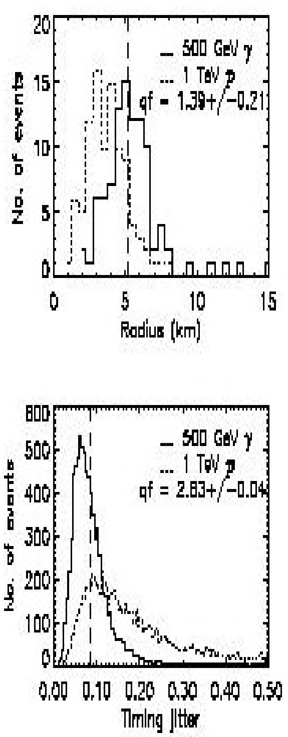
Species Sensitive Parameters in WST
(based on Cerenkov Photon densities)





Species Sensitive Parameters in WST

(based on Cerenkov Arrival Times Photons)



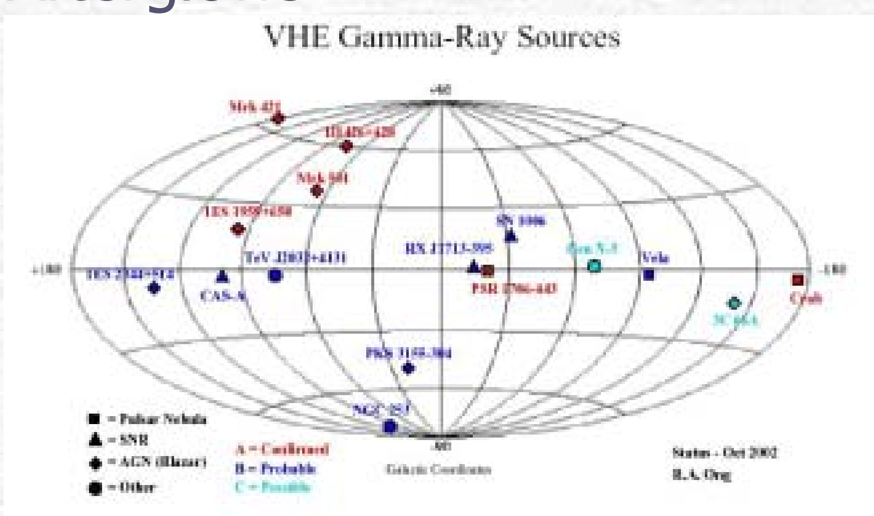
Distributions of three primary species sensitive parameters based on Čerenkov photon timing information *viz.* radius of curvature of the shower front, pulse decay time and relative arrival time jitter. The derived quality factors and the primary energies considered here are indicated.

Table Gamma-hadron separation for showers initiated by 500 GeV γ−rays and 1 TeV protons at Hanle

Parameter	Threshold value	Quality factor	Fraction of accepted γ−rays	Fraction of accepted protons
Shower front curvature	5.2 km	1.39 ± 0.21	0.577	0.173
Decay time of pulse	4.54 ns	1.40 ± 0.12	0.682	0.236
Timing jitter	0.084	2.63 ± 0.02	0.487	0.034
Decay time and jitter	4.54 ns, 0.084	2.25 ± 0.05	0.349	0.024
LDF	0.127	1.53 ± 0.03	0.803	0.276
MDF	0.164	1.24 ± 0.09	0.386	0.097
Flatness parameter	34.8	1.01 ± 0.05	0.963	0.902
LDF and MDF	0.127, 0.164	1.60 ± 0.15	0.338	0.045

Recent Results from TeV Observations

- Blazars
- SNR's: Possible Sources of Galactic Cosmic Rays
- Multi-wavelength Observations of Blazars
- GRB Afterglows



VHE Sky Map, as of October 2002. In the last three years, six new sources have been reported: the supernova remnants CAS-A and RX J1713-3946, the blazars 1ES 1959+650 and H1426+428, the starburst galaxy NGC 253, and the unidentified source TeV J2032+4131.

TeV Source Catalog

Details of 15 VHE sources detected by second generation telescopes

Source	Type	Discovery year	EGRET detection
Galactic			
Crab Nebula	Plerion	1989	yes
PSR 1706-44	Plerion	1995	no
Vela	Plerion	1997	no
SN1006	Shell	1997	no
RXJ1713.7-3946	Shell	1999	no
Cas A	Shell	1999	no
Cen X-3	Binary	1999	yes
Cygnus OB2	Star Cluster	2002	yes
Extra-galactic			
NGC 253	SBG 2.5 Mpc	2002	no
Mkn 421	XBL z=0.031	1992	yes
Mkn 501	XBL z=0.034	1995	no
1ES2344+514	XBL z=0.044	1997	no
PKS2155-304	XBL z=0.116	1999	yes
PKS1959+650	XBL z=0.048	1999	no
3C66A	RBL z=0.44	1998	yes

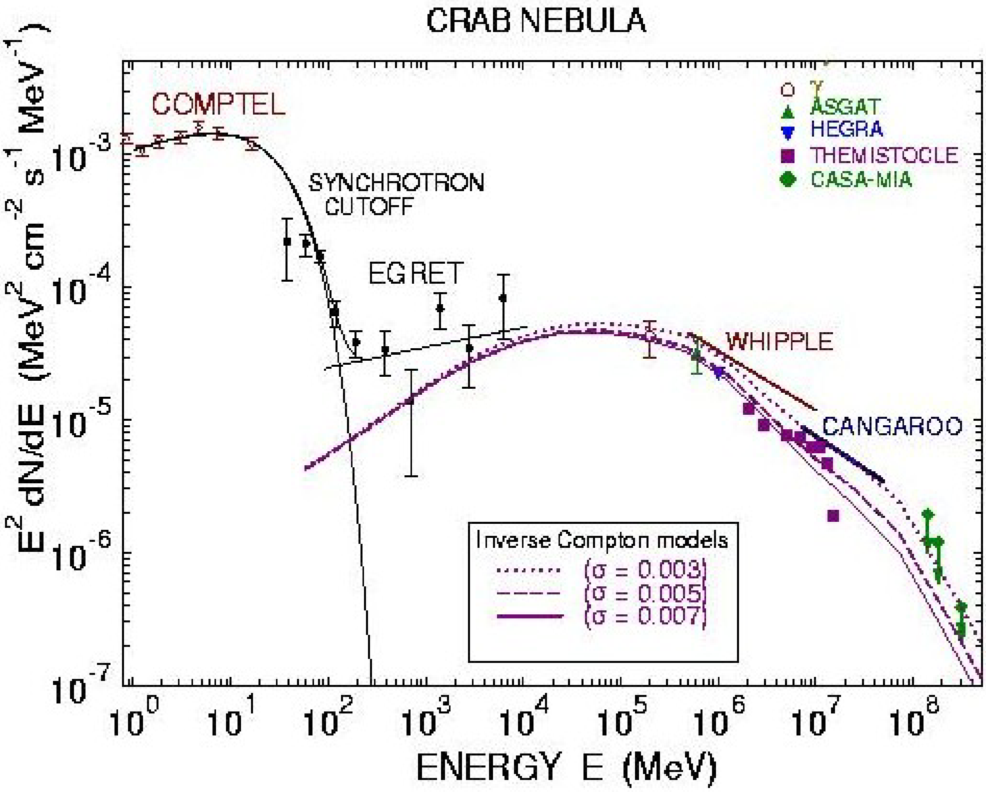
Pulsars and pulsar nebulae:

- ✓Pulsars - rapidly rotating neutron stars left over, e.g., after a supernova explosion - exhibit large electric and magnetic fields and act like dynamos accelerating particles.

- ✓The pulsar-generated outflow - the pulsar wind - interacts with the ambient medium, generating a shock region where particles are accelerated.

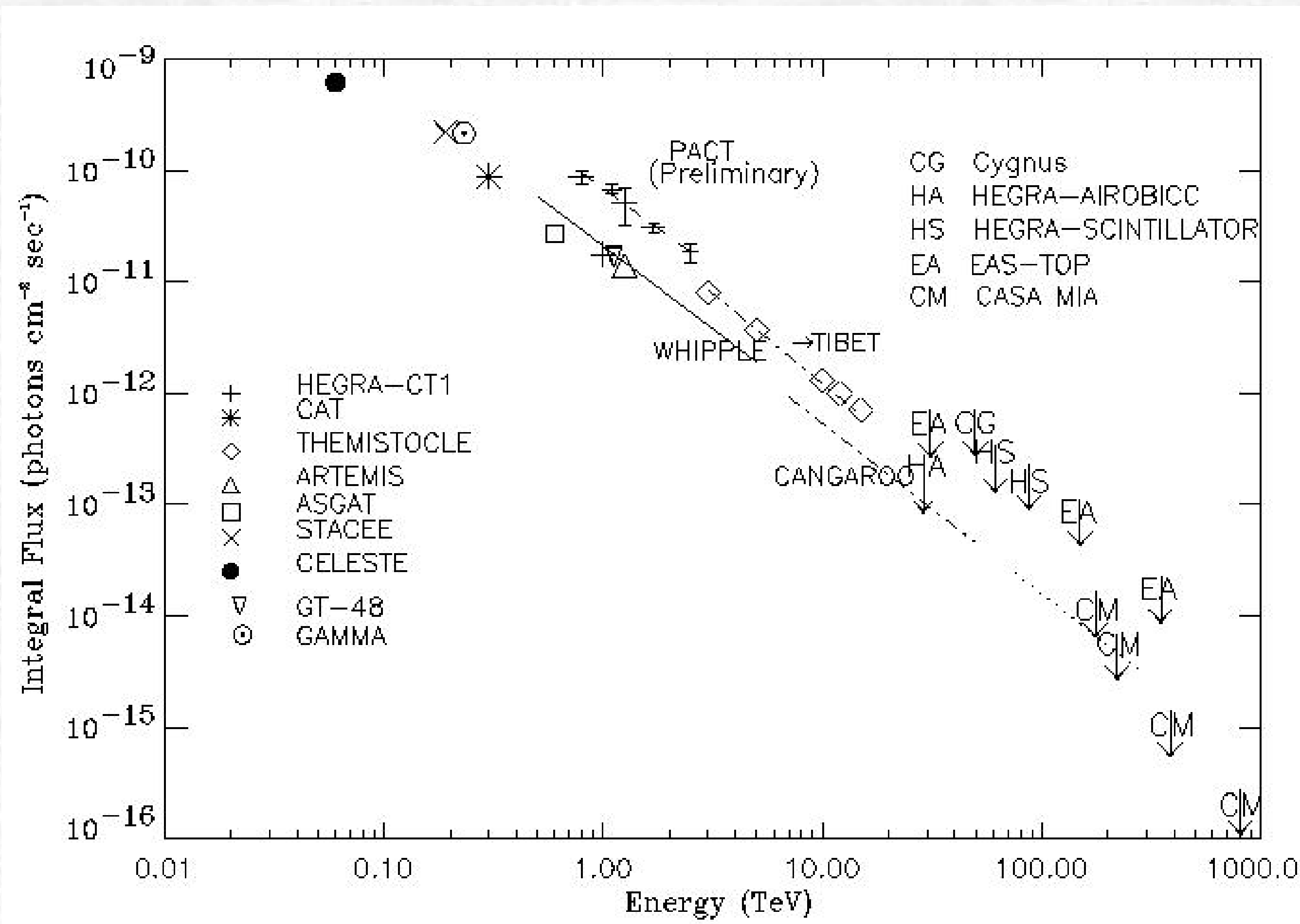
- ✓Such objects will therefore exhibit a pulsed component of radiation - from the immediate vicinity of the pulsar - and an unpulsed component from the shock region and beyond.

- ✓The Crab Nebula is one of the few known TeV emitters of this type, and the best-studied object.

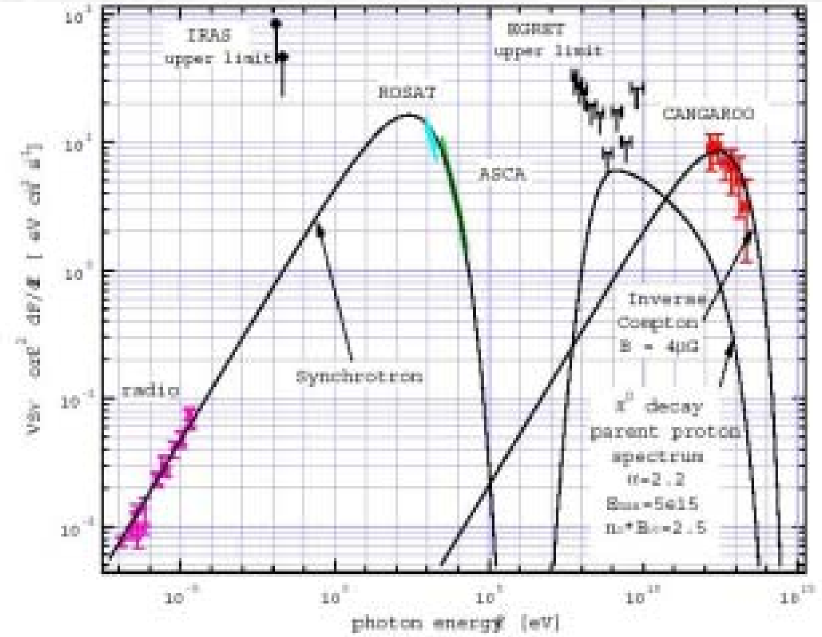


Comparison of gamma-ray measurements of the unpulsed emission from the Crab Nebula and predictions of the synchrotron self-Compton (SSC) model [154]. The Crab spectrum (in terms of E^2 times the differential spectrum) is plotted as a function of energy. The observations above 100 GeV are summarized in Tables 5 and 6.

Crab Nebular Spectrum From PACT



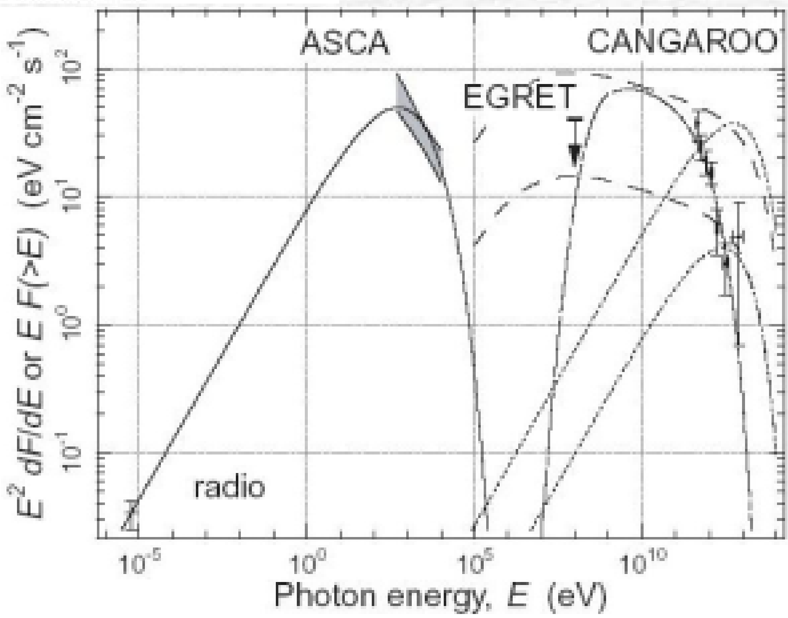
Model fits to SNR spectra



Energy spectrum at the north rim of SN1006 from radio to TeV, and also fitting results based on the shock model.

SN 1006

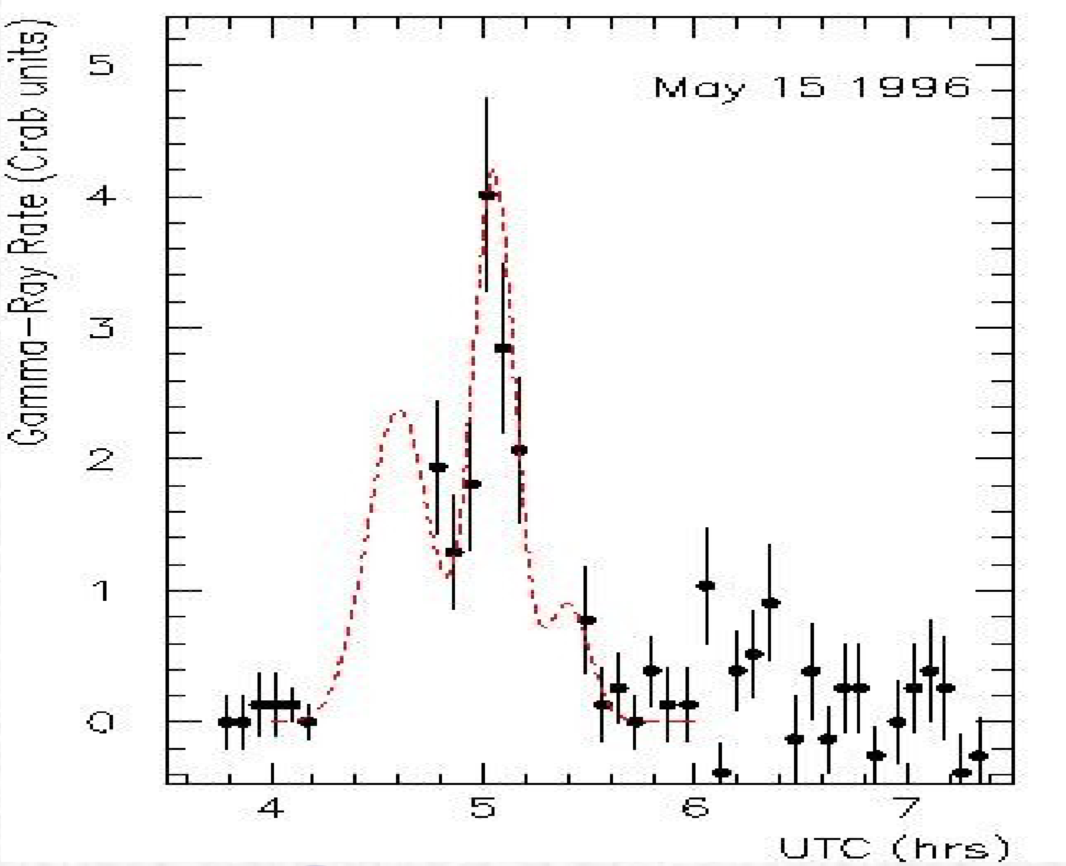
RXJ 1713-3846

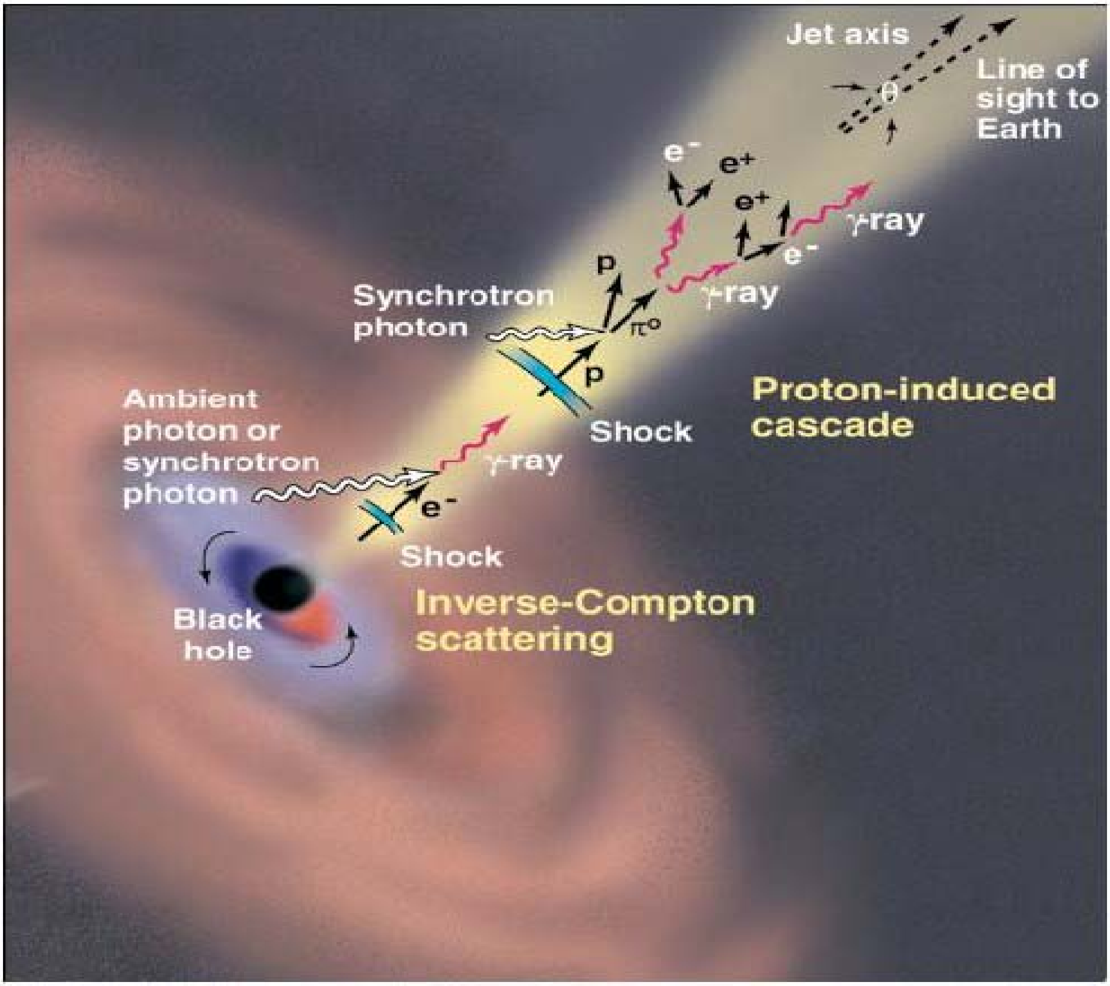


Multi-band emission with models. TeV gamma-ray points are from this work. Lines show model calculations: synchrotron emission (solid line), Inverse Compton emission (dotted lines), bremsstrahlung (dashed lines) and emission from π^0decay (dot-dashed line).

Black holes in the centers of active galaxies:

✓A class of Active galaxies (Blazars) are currently, together with the Crab Nebula, the best-explored sources of TeV gamma-rays, mainly due to the two objects Markarian 421 and 501, which show a large and highly time-variable gamma-ray flux.

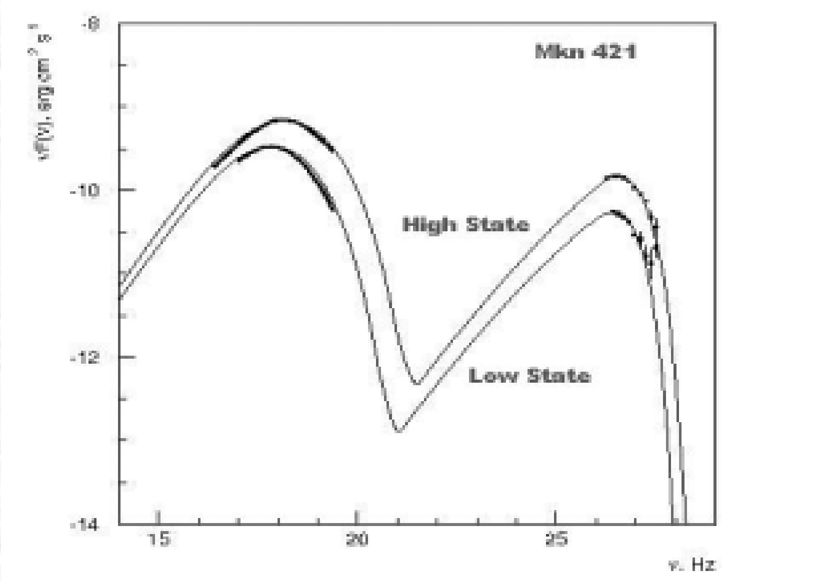


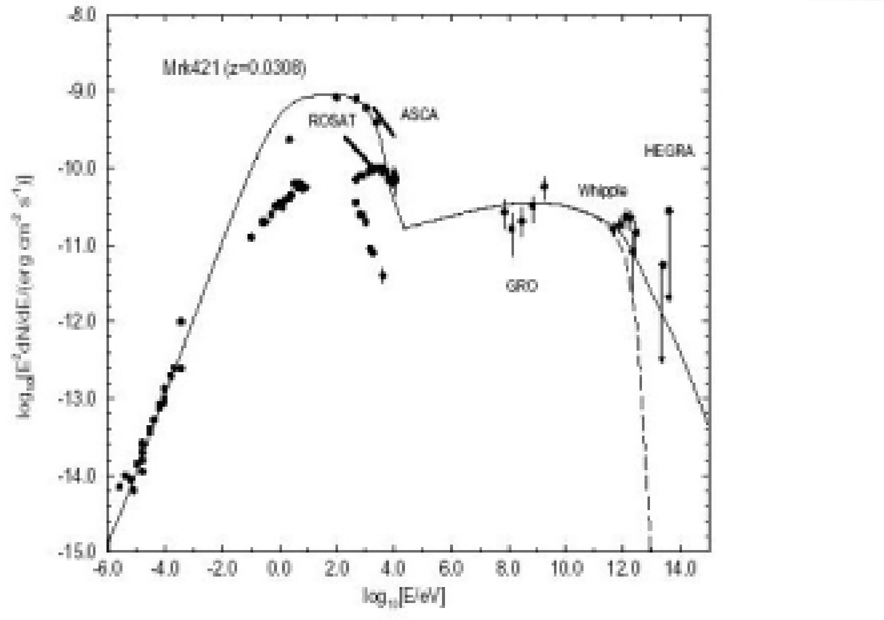


Particle acceleration is likely to take place in small regions of the relativistic jets emerging from the central black hole with a mass of about 10^8 solar masses. Correlations between TeV gamma-rays and nonthermal X-rays point to electrons as the primary nonthermal population. However, the acceleration mechanisms as well as the causes of the fast variability are still unresolved.

Spectral fits to Blazar emission

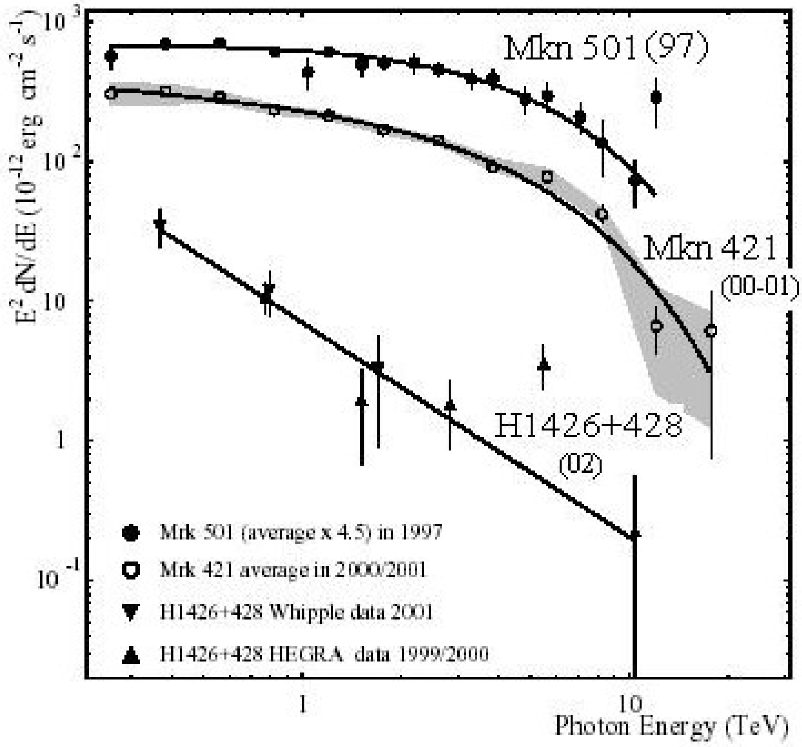
Same cut-off energy of 3.6 TeV in both states of Mkn 421.



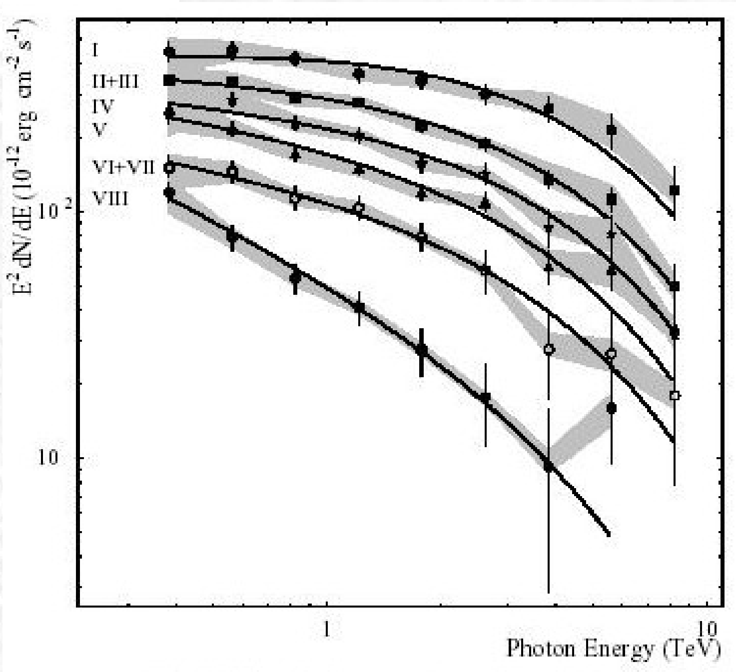


Multifrequency spectrum of Mrk421 obtained from the NED, von Montigny et al. (1994), Punch et al. (1992), Thomas (priv.com.), Kühn (1994) and Karle (1994). The solid line shows the proton blazar model fit for the parameter values in Tab. 1. The dashed line shows the expected flux accounting for external absorption (Stocker et al. 1992)

TeV γ-ray Spectra from Blazars
$dN\gamma / dE \;\alpha\; E^{-\alpha} \exp(-E/E_0)$



Time averaged blazar spectra

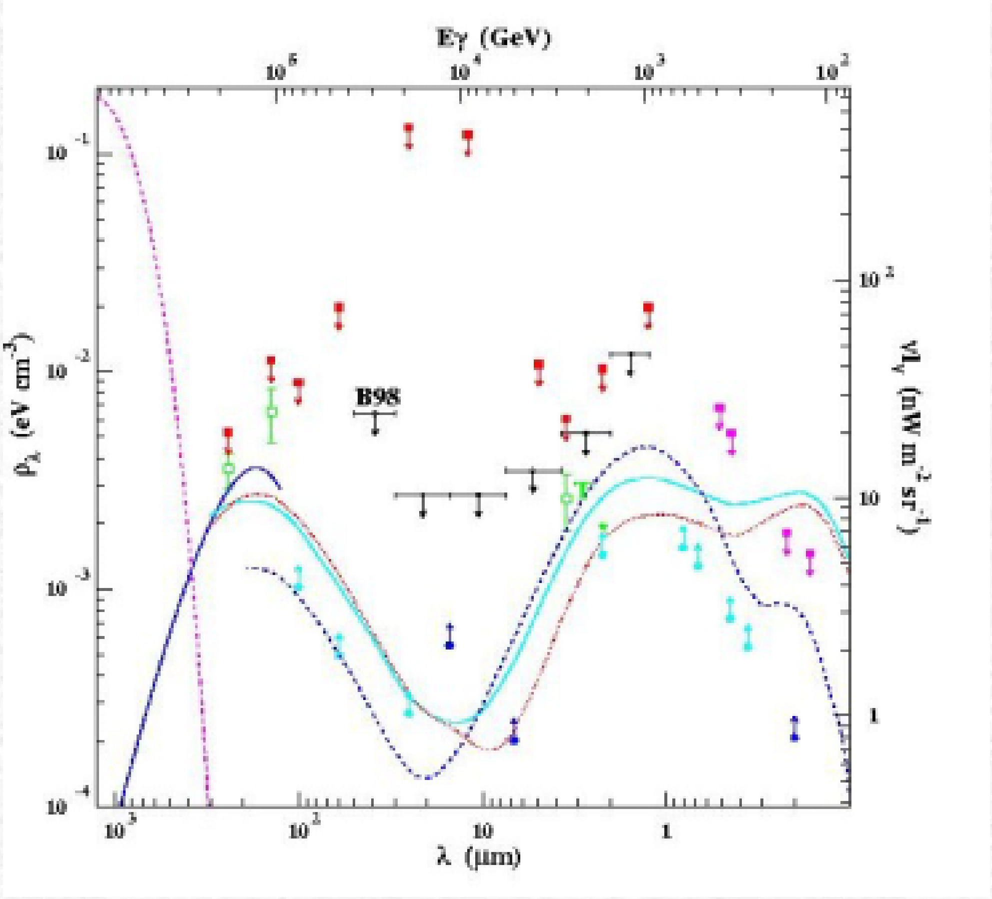


Mkn 421 Spectra (averaged over 5 months) for different flux levels (1.3-10.5 Crab)

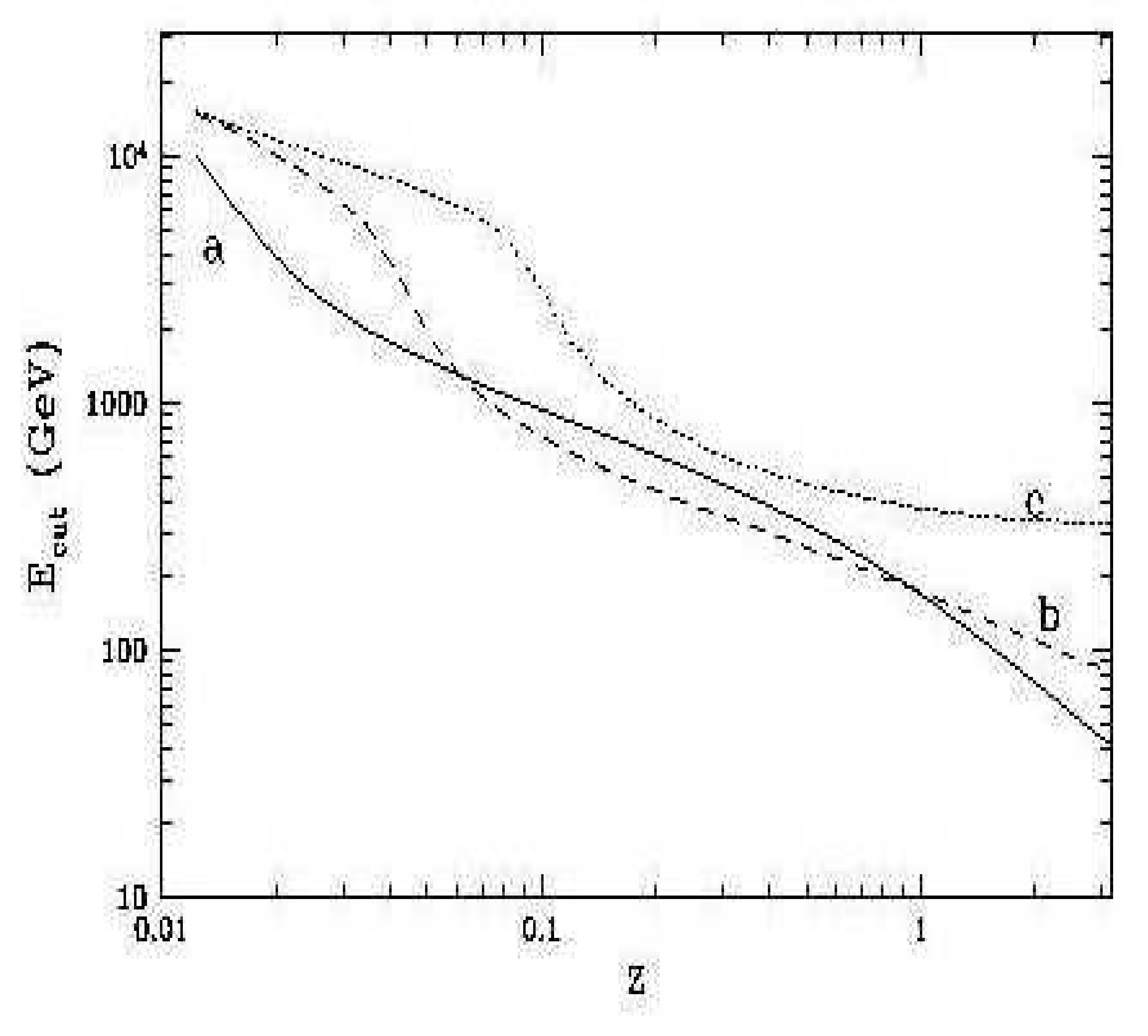
γ-ray propagation in the inter-galactic medium.

$$\gamma + \gamma_{IP} \Rightarrow \mathbf{e^{+}} + \mathbf{e^{-}}$$

Observations of VHE gammas, if done systematically, will also allow to formulate constraints on star formation in the early universe, by measuring the extragalactic infrared radiation field. $\lambda\ (\mu m) \sim 1.24\ E\ (TeV)$



Transparency of the Universe to γ–rays



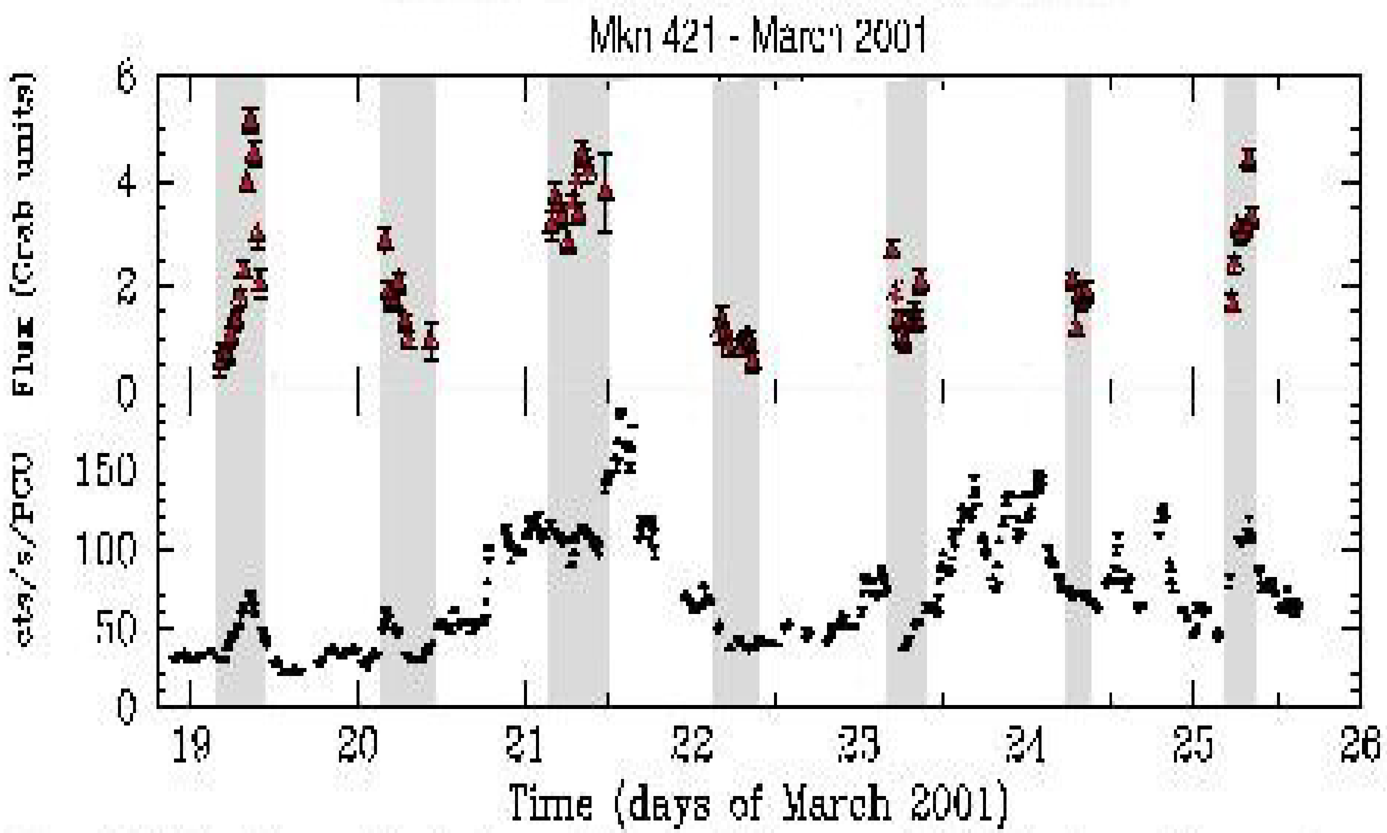
Fundamental Physics

They will further allow searches for the stable lightest supersymmetric particle, expected (if it exists) to annihilate with its own self-conjugate antiparticle into photons in areas of high gravitational field, e.g. in the vicinity of the black holes of galactic centers (including our own).

Quantum gravity effects might become apparent if subtle time differences can be detected in the arrival of gammas from a given source, at different wavelengths. If they occur in nature, ground based Cerenkov detectors have the capability to record such phenomena.

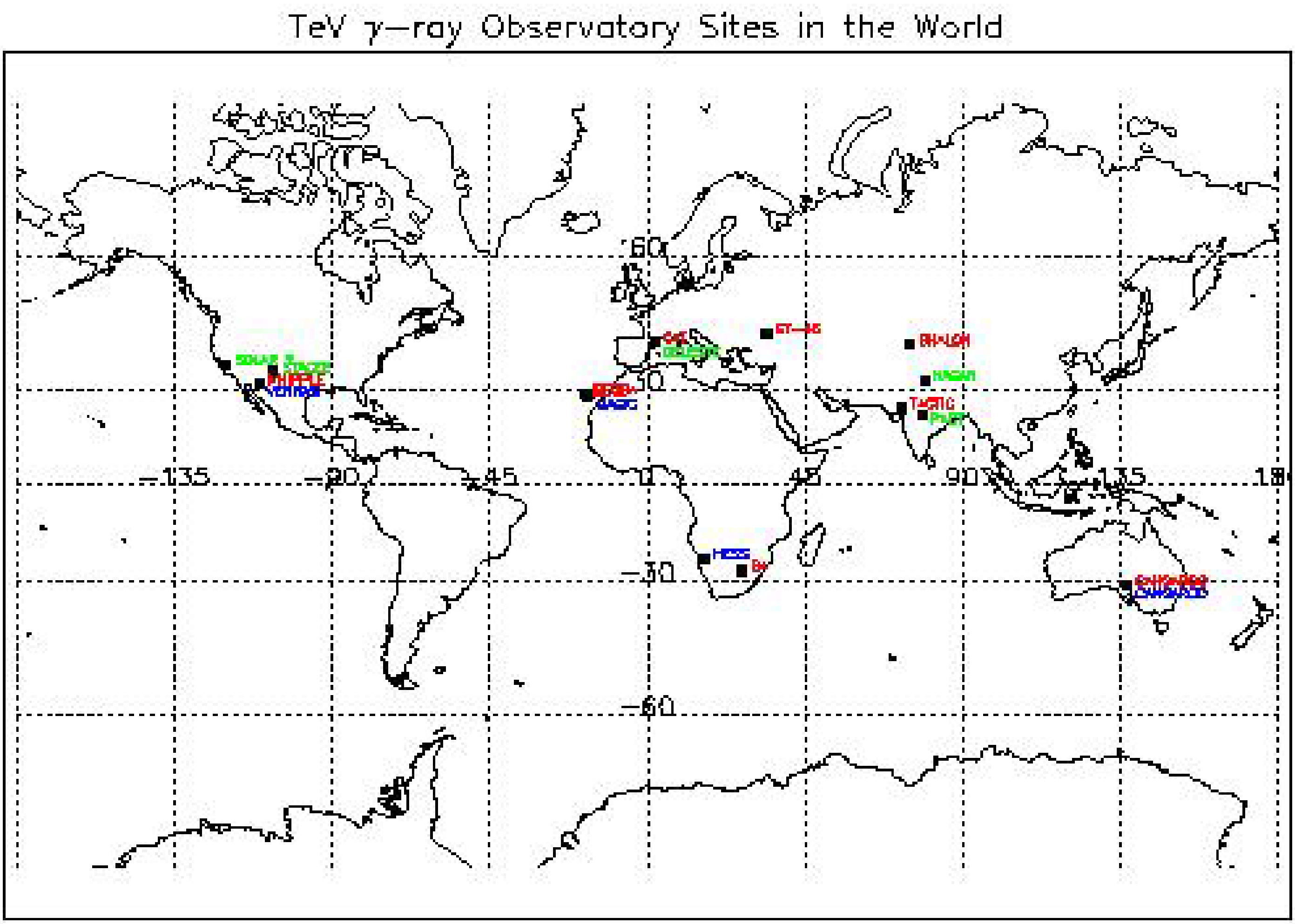
$$\Delta t \sim \xi \,(E/E_{QG})*(L/c)$$

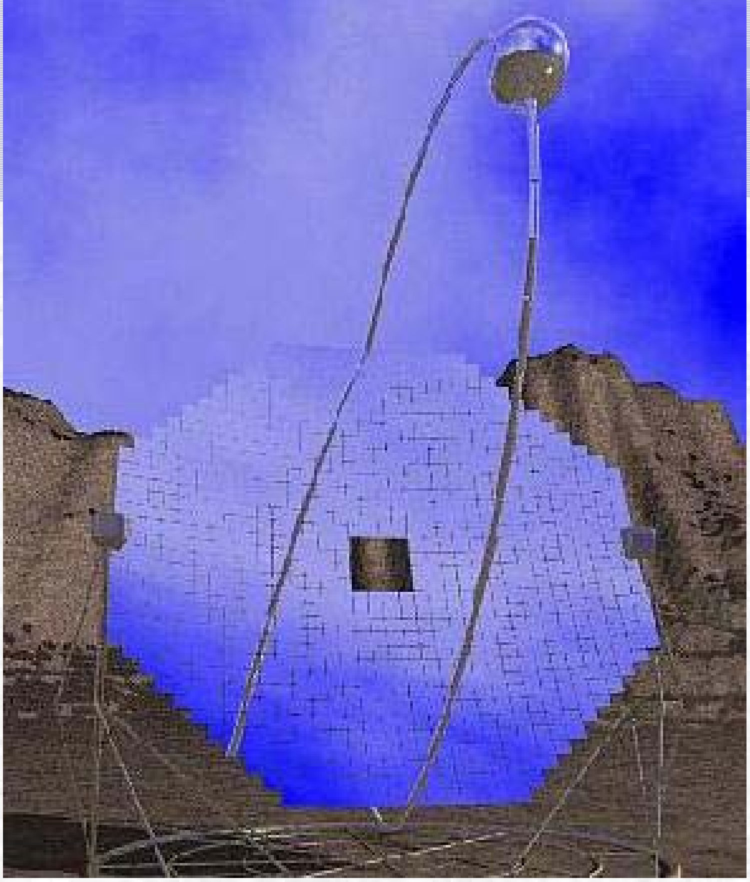
X-γ Correlated Emission



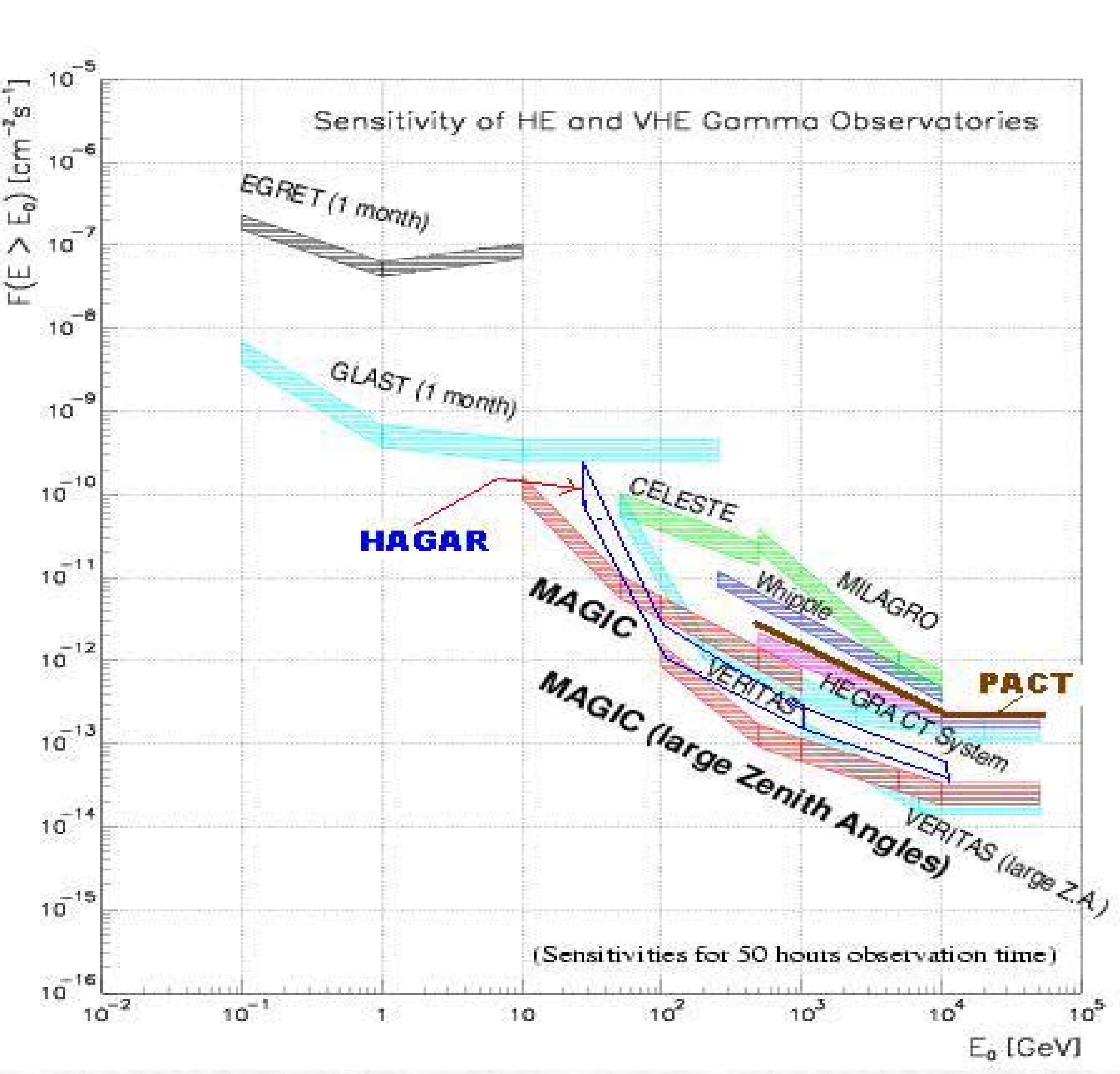
This is the best existing simultaneous X-ray (*RXTE*, bottom) and TeV (Whipple, top) light curves for any blazar (Mkn 421). The correlation between these two bands, separated by a factor of ~10^9 in energy, indicates a link between the synchrotron and Compton components (in the SSC model). However the TeV coverage was only 4-7 hr per day, making it impossible to follow the relation between bands as a flare evolves. We will use six TeV telescopes to cover almost 20 hr per day, allowing flares to be tracked in the TeV almost as well as in the X-rays.

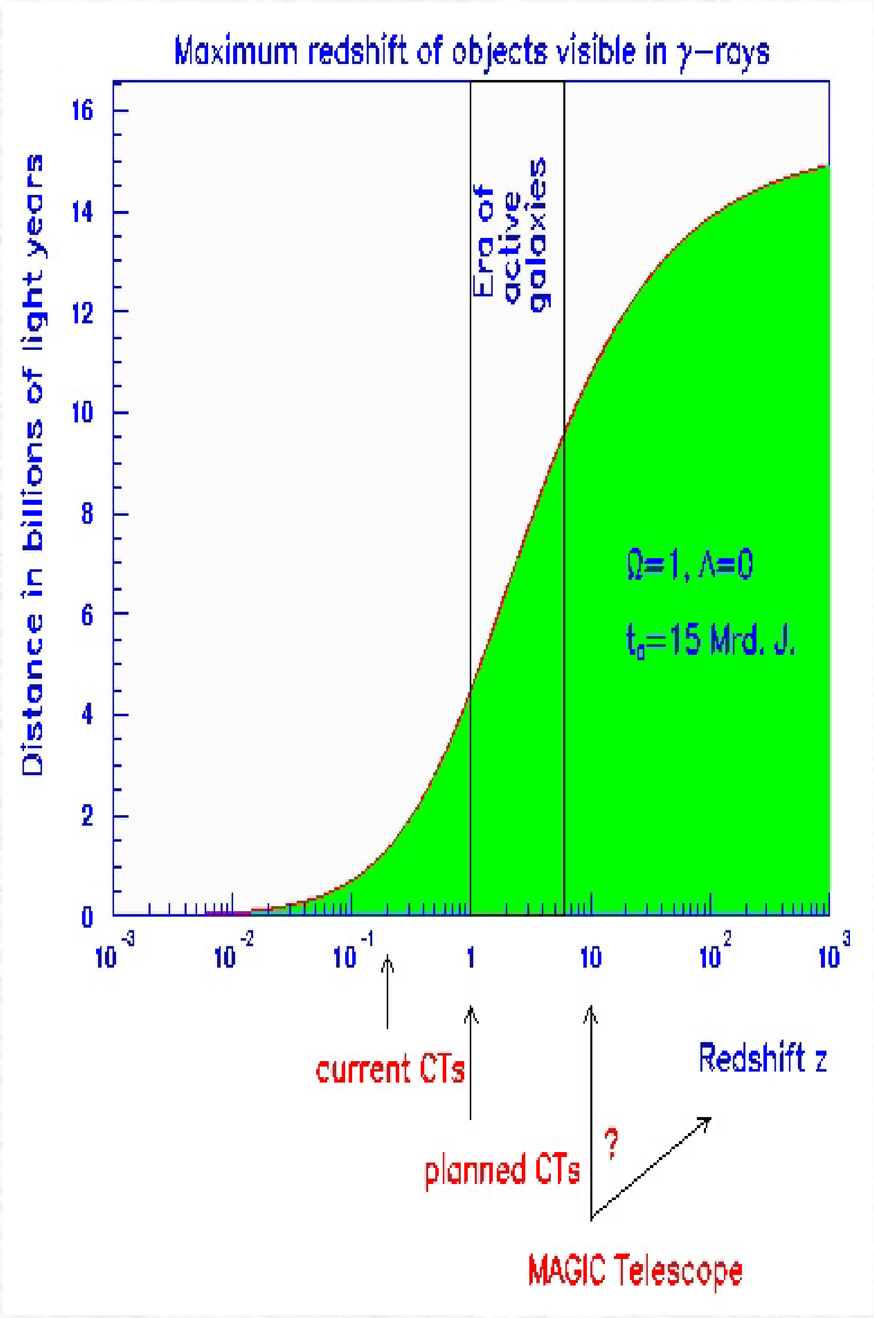
Future TeV γ-ray Observatories





Flux Sensitivity of Present & Future TeV Telescopes




Maximum redshift of objects visible in γ-rays
Distance in billions of light years
16
14
12
10
8
6
4
2
0
10^-3
10^-2
10^-1
1
10
10^2
10^3
Era of active galaxies
Ω=1, Λ=0
t0=15 Mrd. J.
current CTs
planned CTs
?
MAGIC Telescope
Redshift z

Summary

- ACT's based on both imaging & wavefront sampling techniques seem to be having comparable sensitivities.
- The sources detected so far with varying degrees of confidence by different groups can be grouped as follows:

  Confirmed sources:Crab, Mkn 421 & 501, PSR 1706-443, H1426+428, 1ES1959+650

  Probable sources: Vela, 1ES2344+514, SN1006, Cas-A, RXJ1713-3846, TeV J2032, PKS2155-304 & NGC253.

  Possible sources: Cen X-3 & 3C66A.
- The X-ray and TeV γ-ray data from blazars can be well fitted by a homogeneous SSC model.
- However the present data aren't inconsistent with hadronic emission models.
- The SED's of SNR 1006 is consistent with synchrotron emission from non-thermal electrons and an inverse Compton component.
- While RXJ1713-3846 may require protons to be the proginitors.

Future of TeV Astronomy

- Very high energy γ-astronomy is looking up and has a lot of promise especially during the GLAST/GBM era, primarily because of the overlapping energy bands.
- New techniques of background rejection that have been developed as well as superior angular resolution will lead to unprecedented sensitivity for the ground based ACT's.
- Very low energy thresholds are achieved either by using large mirror areas or choosing high altitude sites. This provides a good overlap with the satellite borne γ – ray detectors like GLAST.

- The catalog of known sources is growing and our knowledge of specific source properties has significantly improved over the last few years.
- With the commissioning of CANGAROO, HESS, MAGIC, VERITAS and HAGAR one may hope for a break through in the understanding of atleast some of the energetic γ-ray sources.

Thank You for your attention